# Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979–2008

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[1] Sea ice conditions and melt season duration within the Canadian Arctic Archipelago (CAA) were investigated from 1979–2008. The CAA is exhibiting statistically significant decreases in average September total sea ice area at −8.7% decade$^{-1}$. The melt season duration within the CAA is increasing significantly at 7 days decade$^{-1}$. 2008 represented the longest melt season duration within the CAA over the satellite record at 129 days. Average September multi-year ice (MYI) area is decreasing at −6.4% decade$^{-1}$ but has yet to reach statistical significance as a result of increasing MYI dynamic import from the Arctic Ocean. Results also find that the Western Parry Channel (WPC) region of the Northwest Passage (NWP) will continue to be susceptible to MYI as the transition to a summer-time sea ice free Arctic continues. The processes responsible for the temporary clearing of the WPC region of the NWP in 2007 were also identified. **Citation:** Howell, S. E. L., C. R. Duguay, and T. Markus (2009), Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979–2008, *Geophys. Res. Lett.*, *36*, L10502, doi:10.1029/2009GL037681.

## 1. Introduction

[2] From 1979–2005, the Arctic melt season duration has increased by approximately 2 weeks decade$^{-1}$ [*Stroeve et al.*, 2006]. Both sea ice extent and area within the CAA from 1979–2006 have exhibited decreases, but only the latter was found to be statistically significant [*Parkinson and Cavalieri*, 2008]. The connection between increased melt season duration and sea ice decreases, particularly in September, have led to considerable speculation about exploitation of the NWP through the CAA (Figure 1) for commercial shipping.

[3] Caution in the interpretation of these decreases within the CAA is warranted because i) the M'Clintock Channel and Franklin regions act as a drain-trap for MYI [*Howell et al.*, 2008a] and ii) there is often an inventory of seasonal first year ice (FYI) that survives the melt season within the CAA [*Melling*, 2002; *Howell et al.*, 2008a]. Longer melt seasons as detected by QuikSCAT from 2000–2007 corresponded to decreases in the inventory of FYI following the melt season but dynamic MYI import persisted [*Howell et al.*, 2008b]. Unfortunately, the QuikSCAT data record is too short for long-term trend analysis. In this brief note we make use of the longer passive microwave Scanning Multichannel Microwave Radiometer (SMMR)-Special Sensor Microwave/Imager (SSM/I) time series and the Canadian Ice Service Digital Ice Chart Archive (CISDA) to explore links between the sea ice conditions and melt season duration within the CAA from 1979–2008.

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## 2. Data and Methods

[4] Average September total and MYI area were extracted from the CISDA. The CISDA consists of regional ice charts that are derived weekly, from the integration of data from a variety of sources, including surface observations and aerial and satellite reconnaissance [*Canadian Ice Service*, 2007]. Typically, average September SMMR-SSM/I sea ice concentrations are used for long-term trend analysis but retrieval algorithms have difficulty during this time period and the narrow channels within the CAA also contribute to significant land contamination. Therefore, we compared average September total ice area within the CAA between CISDA and SMMR-SMM/I sea ice concentrations retrieved by the NASA Team algorithm [*Cavalieri et al.*, 2008] with no additional processing of the data. The interannual variability is virtually identical (correlation coefficient (r), r = 0.94) but the SMMR-SSM/I ice area is 20% lower on average (Figure 2). As a result, we have chosen to utilize the CISDA because they provide a more representative estimate of September sea ice conditions within the CAA.

[5] The CISDA were also used to estimate the inventory of FYI at the end of the melt season and the amount of MYI dynamically imported within the CAA by a method described by *Howell et al.* [2008b]. Briefly, by definition FYI is promoted to MYI on October 1st and therefore, the last week of September usually represents the amount of MYI that survived the melt season. The sea ice in the CAA is virtually immobile and landfast on April 1st and MYI dynamic import within the CAA can be estimated by taking the difference between MYI area on the last week of September from MYI area on April 1st. Positive values represent MYI import and negative values represent MYI than has been exported or melted. The uncertainty associated with this value is that during the melt season some MYI within the CAA can be lost due to melt or export across the M'Clure Strait, Amundsen, Jones Sound, and/or Lancaster Sound boundaries. Loss across the northern QEI is negligible because of persistence from the polar pack [*Melling*, 2002]. Positive values determined by this method only represent the minimum amount of MYI imported into the CAA. The inventory of FYI at the end of the melt season can be estimated by subtracting MYI area the week after October 1st from MYI area the week before October

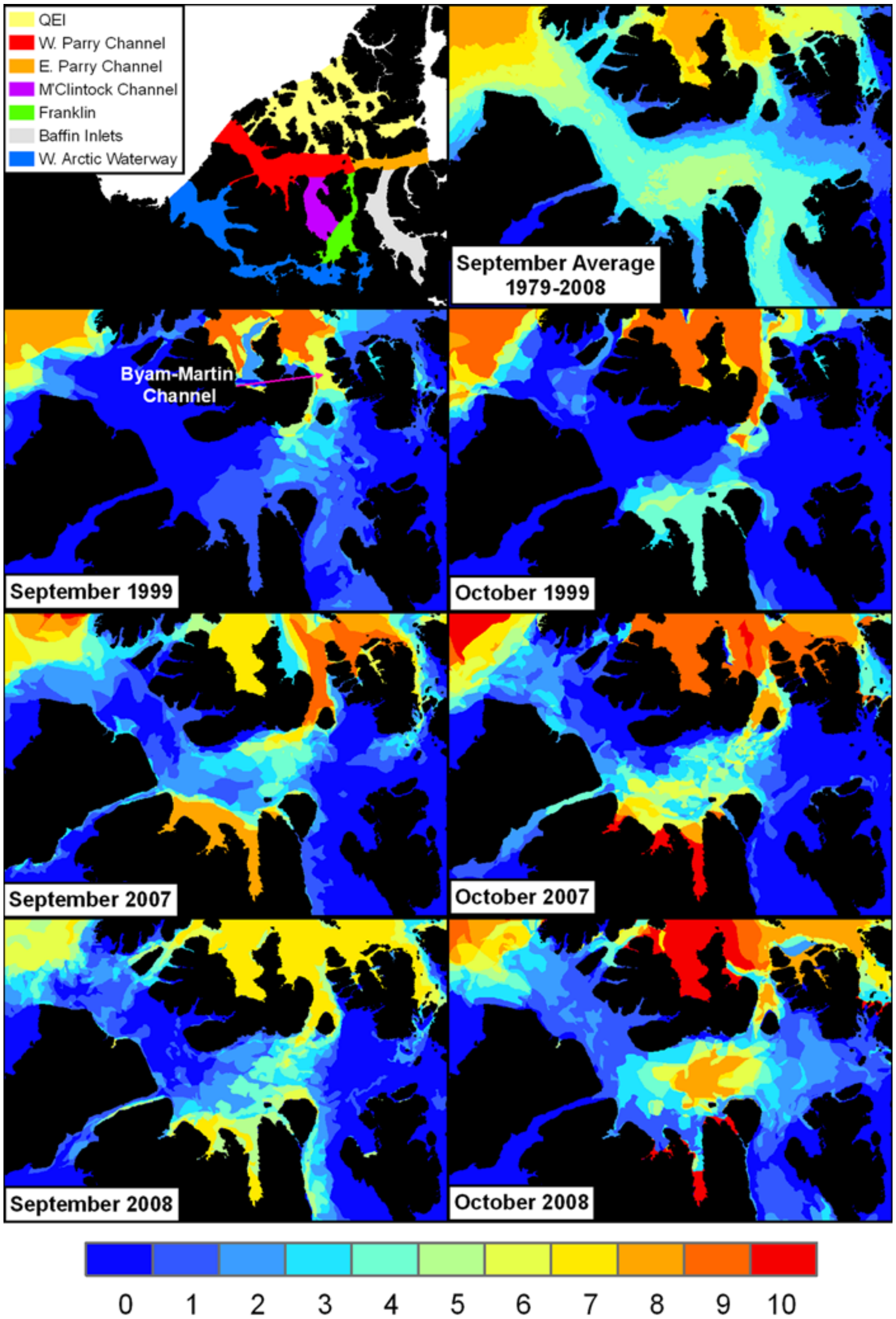


**Figure 1.** Map of the Canadian Arctic Archipelago and its sub-regions. Also shown is the spatial distribution of the average 1979–2008 September MYI concentration (in tenths) and average September and October MYI concentration (in tenths) for light MYI years within the Western Parry Channel region of the Northwest Passage.

1st. Positive values represent aging or dynamic import and negative values represent export or melting. The first uncertainty with this estimate is that MYI dynamic import/export can occur during this 1-week time window. However, ice motion is slow and intermittent within the CAA therefore unless rapid import/export takes place there will not be considerable change within this 1-week. Secondly, although likely small, the FYI being promoted to MYI may not have originated within CAA.

[6] Melt and freeze dates were determined from an updated version of the PMW algorithm described by *Stroeve et al.* [2006]. The strategy of the method is to take advantage of several indicators of melt and freeze onset inherent in the data and explore their agreement. Some of those indicators are similar to earlier works by *Smith* [1998] and *Drobot and Anderson* [2001]. The combined approach builds on the strength of multiple indicators as they are each sensitive to different features of melt (freeze). The agreement of these different indicators is utilized. The strength of the melt (freeze) signal is determined by summing up the normalized magnitude for each indicator. The day with the greatest sum is the first choice for the melt (freeze) onset day. In this paper, the first event of melt (freeze) is identified as the day of the first occurrence of melt (freeze) indepen-

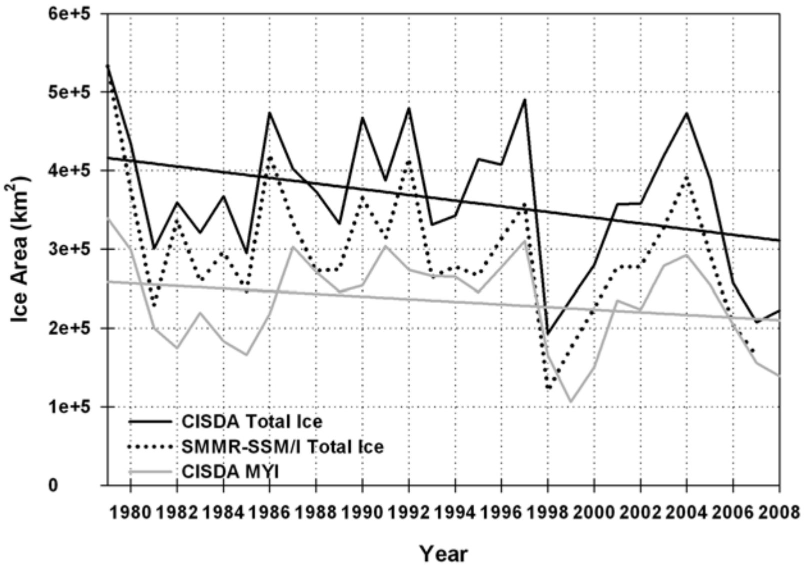


**Figure 2.** Time series of average monthly September total ice and multi-year ice area as determined from the CISDA within the Canadian Arctic Archipelago, 1979–2008. The time series of average monthly September total ice area as determined from the SMMR-SMM/I sea ice dataset within the Canadian Arctic Archipelago, 1979–2007 is also shown.

dent of whether temperatures remain above (below) freezing or not.

[7] Trend analysis was performed on CISDA sea ice data and the SMMR-SSM/I melt/freeze variables for the CAA and sub-regions using the method of least squares fit regression from 1979–2008. The significance of each trend and correlation was tested using a standard F-test test at the 95% confidence level.

## 3. Results and Discussion

### 3.1. Trends in Sea Ice Area and Melt Season Duration

[8] The CAA is exhibiting significant decreases in average September total sea ice area at a rate of $-3.62 \times 10^3$ km$^2$ year$^{-1}$ ($-8.7$% decade$^{-1}$) (Figure 2 and Table 1). All the CAA sub-regions also exhibit negative trends but only Baffin Inlet is statistically significant (Table 1). *Moore* [2006] using the SMMR-SSM/I dataset also reported decreases in the Baffin Inlet region from 1979–2004. 1998 represents the lowest average September total sea ice area at $193 \times 10^3$ km$^2$ and is closely followed by 2007 ($207 \times 10^3$ km$^2$) and 2008 ($222 \times 10^3$ km$^2$) (Figure 2). Average September MYI area is decreasing at $-1.67 \times 10^3$ km$^2$ year$^{-1}$ ($-6.4$ % decade$^{-1}$) but has yet to reach statistical significance (Figure 2 and Table 1). All sub-regions also exhibit negative MYI trends but only Baffin Inlet and Franklin are significant (Table 1). The three lowest average September MYI areas are 1999 ($106 \times 10^3$ km$^2$), 2008 ($139 \times 10^3$ km$^2$), and 2000 ($150 \times 10^3$ km$^2$) (Figure 2).

[9] The melt season duration within the CAA is increasing significantly at 7 days decade$^{-1}$ attributed to both an earlier melt ($-3.1$ days decade$^{-1}$) and later freeze (3.9 days decade$^{-1}$) (Table 2). All sub-regions are experiencing significant increases in the melt season duration except the Western Arctic Waterway (Table 2). 2008 represents the longest melt season duration within the CAA of 129 days, eclipsing the previous record of 123 days reached in 1998.

[10] The inverse correlation between average September total ice area and melt season duration for the CAA is strong at $-0.71$ (Table 3). All sub-regions except the Western Arctic Waterway are also experiencing a fairly strong correlation of $-0.6$ (Table 3). However, for average September MYI area, the correlation to melt duration is much smaller (Table 3). Based on these correlations, we suggest that long

**Table 1.** Slopes of the Lines of Linear Least Squares Fit Through Average September Total Ice and Multi-year Ice Area Within the Canadian Arctic Archipelago, 1979–2008[a]

| | Total Ice Area Trend | | MYI Area Trend | |
|---|---|---|---|---|
| Region | Trend (km$^2$ year$^{-1}$) | Percent per Decade | Trend (km$^2$ year$^{-1}$) | Percent per Decade |
| Canadian Arctic Archipelago | **−3627** | **−8.7** | −1666 | −6.4 |
| Queen Elizabeth Islands | −421 | −2.5 | −294 | −2.4 |
| Western Parry Channel | −880 | −8.2 | −47 | −0.8 |
| Eastern Parry Channel | −146 | −15.4 | −22 | −7.0 |
| M'Clintock Channel | −412 | −10.0 | −299 | −11.0 |
| Franklin | −417 | −17.5 | **−309** | **−24.4** |
| Baffin Inlet | **−1101** | **−20.5** | **−662** | **−25.8** |
| Western Arctic Waterway | −249 | −24.9 | −33 | −7.9 |

[a]Values in bold are statistically significant at the 95% or higher confidence interval.

**Table 2.** Slopes of the Line of the Linear Least Squares Fit Through Melt Onset, Freeze Onset, and Melt Duration Within the Canadian Arctic Archipelago, 1979–2008[a]

| Region | Melt Trend | Freeze Trend | Melt Duration Trend |
|---|---|---|---|
| Canadian Arctic Archipelago | **−3.1** | **3.9** | **7.0** |
| Queen Elizabeth Islands | **−3.7** | 2.9 | **5.6** |
| Western Parry Channel | **−3.6** | 3.0 | **6.5** |
| Eastern Parry Channel | −5.1 | **5.5** | **10.6** |
| M'Clintock Channel | −3.4 | **4.4** | **7.7** |
| Franklin | −3.2 | **6.3** | **9.5** |
| Baffin Inlet | **−4.7** | **7.3** | **12.0** |
| Western Arctic Waterway | −1.2 | 2.6 | 3.8 |

[a]Values in bold are statistically significant at the 95% or higher confidence interval. Values are given in days decade$^{-1}$.

melt seasons are reducing the seasonal FYI component of the CAA ice matrix but have yet to influence MYI because it is more difficult to melt. Interestingly, while 2008 represented the longest melt season on record within the CAA, it does not correspond to the year with the lowest amount of MYI. In order to physically explain the latter correlations, we now look at the long-term changes in the melt duration with respect to the source of CAA MYI.

### 3.2. Changes in the Source Input of CAA Multi-year Ice

[11] The time series of the source of CAA MYI and melt season duration from 1979–2008 is presented in Figure 3. FYI aging is the dominant contribution to the CAA's MYI composition up until 1994 but more dynamic MYI import is occurring in recent years. There is also a significant inverse correlation between FYI aging to melt season duration of $r = -0.48$. From 1979 to 1994 the shorter melt durations and subsequently reduced open water areas restrict ice movement within the CAA whereas, the reverse is true for the long melt seasons in recent years (Figure 3).

[12] A heavily MYI congested CAA prevented MYI import for 2005 and 2006 despite the long melt season [*Howell et al.*, 2008b] but 2007 and 2008 are once again experiencing MYI increases (Figure 3). The 2008 melt season was very long but summertime air temperatures where not anomalously warm (not shown) resulting in some FYI aging. However, the majority of the MYI increases began the week of October 1st from dynamic import (Figure 1). The long melt season of 2008 weakened the QEI ice barriers facilitating continued MYI import from the Arctic Ocean and rapid flushing of MYI through the CAA. During October, MYI continued to flow through the CAA eventually migrating to the M'Clintock Channel and Franklin regions by late-October/early-November and more MYI is now present within the CAA following the 2008 melt season (not shown). The CAA is recovering from low 2007 conditions but this is mostly attributed to MYI dynamic import in October and November, not FYI aging.

### 3.3. Continued Multi-year Flow Into the Northwest Passage

[13] The majority of the CAA's MYI is generated within or imported into the QEI region from the Arctic Ocean [*Melling*, 2002; *Kwok*, 2006; *Howell et al.*, 2008a; *Agnew et al.*, 2008], but increased MYI through-flow will also be felt in the Parry Channel regions to the south. An examination of MYI conditions within the CAA in September and October for low MYI years (e.g., 1999, 2007, and 2008) illustrates that the majority of MYI flow from the QEI occurs into the WPC via the Byam-Martin Channel (BMC) (Figure 1). The QEI and WPC regions also exhibit the smallest decreases in MYI despite significant increase in the melt season duration (Tables 1 and 2) providing evidence that the WPC is very susceptible to MYI from the QEI. Very little net MYI import occurs from the Arctic Ocean into the WPC via the M'Clure Strait (Figure 1). The MYI tongue of the Arctic Ocean polar pack often extends and retreats into the CAA via the M'Clure Strait but net sea ice import seems to be an anomalous occurrence. This was confirmed by *Kwok* [2006] and *Agnew et al.* [2008] who found a net export of ice from the M'Clure Strait from 1997–2007. Instead, the periodic extending and retreating of the polar pack tongue into the M'Clure Strait pushes MYI in the WPC down into the M'Clintock and Franklin regions [*Howell et al.*, 2008a]. Continued flow of MYI from the QEI into the WPC via BMC has negative implications for practical utilization of the NWP.

### 3.4. Removal of Multi-year Ice Within the Northwest Passage in 2007

[14] One of the striking outcomes of the 2007 CAA melt season was the temporary clearing of the WPC route through the NWP for the first time during the satellite era. However, is it reasonable to assume this trend will continue? The region has contained high concentrations of MYI since the 1970s (Figure 1) and we have provided evidence for longer melt seasons facilitating continued import of MYI to the region. Moreover, 2007 was not even the longest melt season within the CAA.

[15] The removal of MYI within the WPC region of the NWP during 2007 can be attributed to the following sequence of events: preconditioned thinning of MYI in the region, anomalous temperatures facilitating rapid melt, and an atmospheric circulation pattern preventing MYI from transiting across the WPC after being flushed from the QEI. Very little MYI replenishment occurred in this region since 2004 and thus MYI has been slowing ablating over the course of several years [*Howell et al.*, 2008b]. This condi-

**Table 3.** Correlation Coefficient Between the Timing of Melt Onset, Freeze Onset and the Melt Season Duration and Average September Total and Multi-year Ice[a]

| | Total Ice | | | Multi-Year Ice | | |
|---|---|---|---|---|---|---|
| Region | Melt Onset | Freeze Onset | Melt Duration | Melt Onset | Freeze Onset | Melt Duration |
| Canadian Arctic Archipelago | **0.50** | **−0.69** | **−0.71** | 0.17 | **−0.53** | **−0.42** |
| Queen Elizabeth Islands | **0.48** | **−0.50** | **−0.65** | 0.36 | **−0.39** | **−0.50** |
| Western Parry Channel | 0.22 | **−0.72** | **−0.62** | 0.14 | **−0.60** | −0.31 |
| Eastern Parry Channel | **0.48** | **−0.60** | **−0.67** | **0.44** | **−0.54** | **−0.61** |
| M'Clintock Channel | 0.28 | **−0.68** | **−0.62** | 0.01 | **−0.62** | **−0.40** |
| Franklin | **0.55** | **−0.56** | **−0.68** | **0.41** | **−0.55** | **−0.59** |
| Baffin Inlet | **0.45** | **−0.47** | **−0.60** | 0.23 | **−0.44** | **−0.43** |
| Western Arctic Waterway | 0.16 | −0.25 | −0.26 | 0.07 | −0.22 | −0.17 |

[a]Values in bold are statistically significant at the 95% or higher confidence interval.

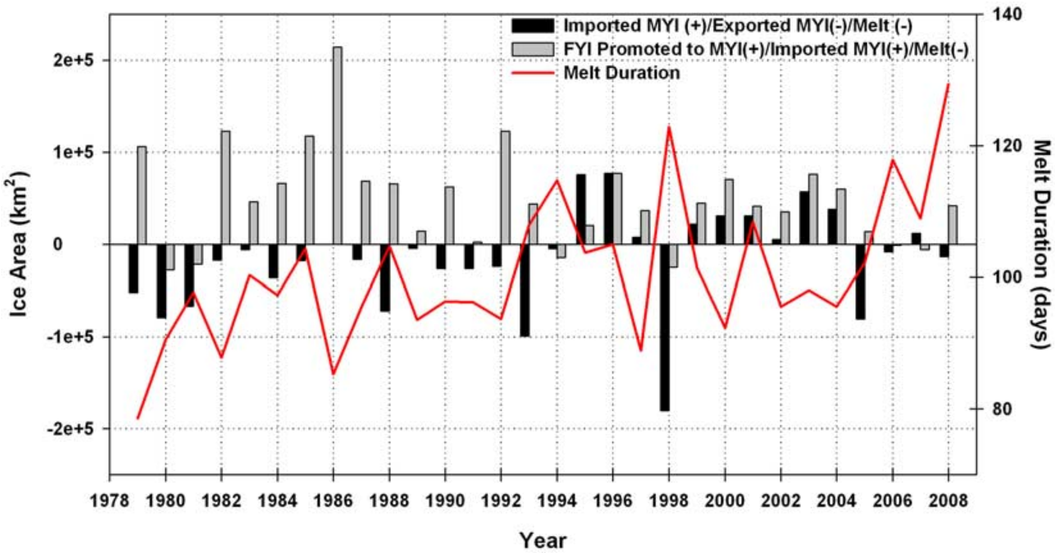


**Figure 3.** Time series of changes in the amount of first-year ice promoted to multi-year ice, dynamically imported multi-year ice, and the melt duration within the Canadian Arctic Archipelago, 1979–2008.

tioned the MYI such that the anomalously warm temperatures of 2007 rapidly removed the already weakened MYI. Average air temperatures for July and August in the WPC for 2007 were approximately 2°C higher than normal (not shown). Finally, ice motion is typically parallel to sea level pressure (SLP) isobars [*Thorndike and Colony*, 1982] and following removal in 2007, the anomalously high SLP over the Beaufort Sea for 2007 prevented MYI streaming through BMC from crossing the WPC, instead it travelled along the coast of Melville Island (Figures 1 and 4).

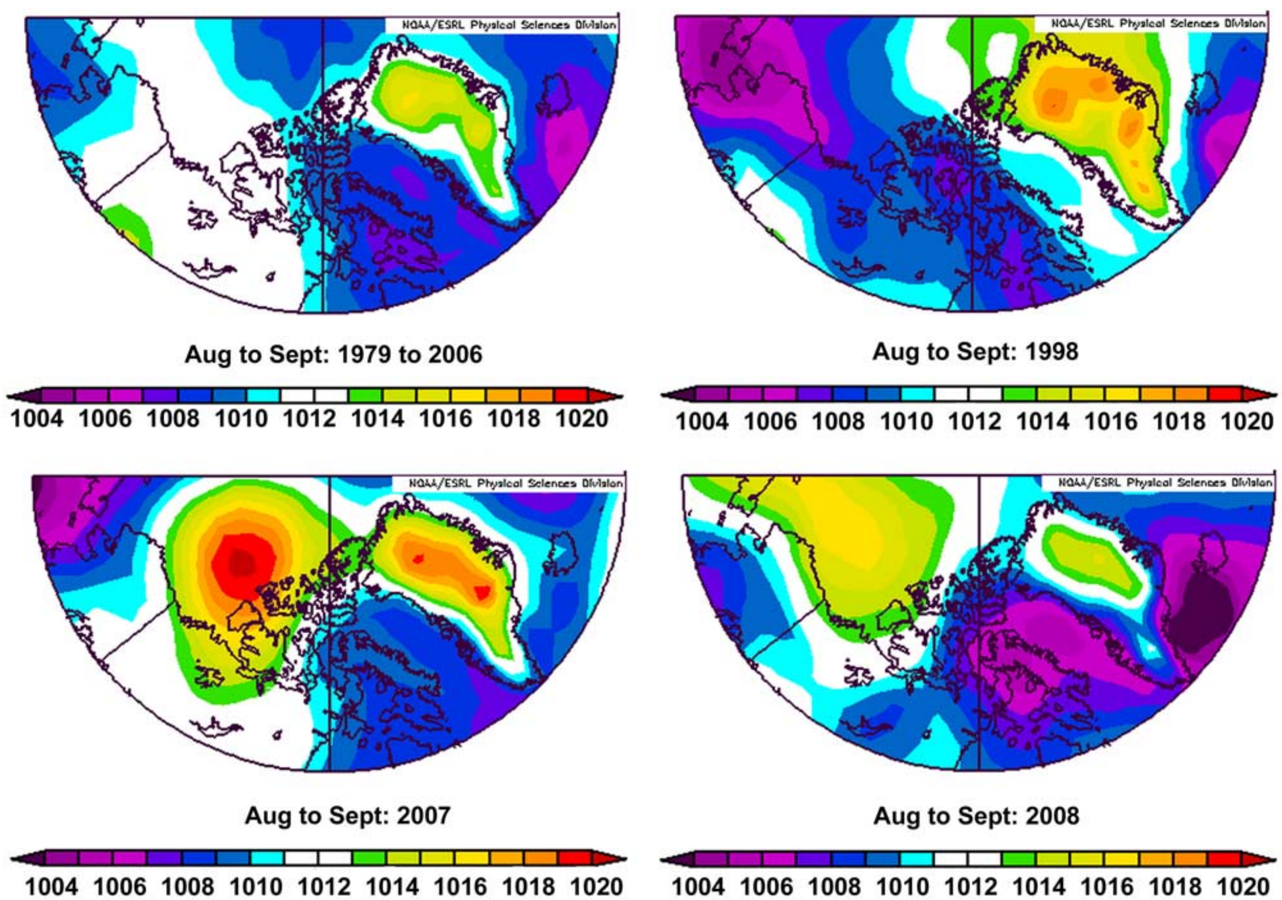


**Figure 4.** Average August–September SLP (mb) over the Canadian Arctic Archipelago for (top left) 1979–2006, (top right) 1998, (bottom right) 2007 and (bottom left) 2008. Data is from NCEP/NCAR Reanalysis as described by *Kalnay et al.* [1996].

[16] The difference between 2007 and 1998 within the WPC region of the NWP was MYI slowly ablating without replenishment late into September (not shown). The average September air temperature in the WPC during 1998 was the warmest ever recorded since 1979 (not shown). As a result, the MYI in the WPC was eventually removed late in 1998 however new ice began to form soon afterward. Anomalous winds from the south prevented MYI import from the QEI (Figure 4) setting up record low MYI conditions for 1999 (Figure 1). In 2008, temperatures were not anomalously warm compared to 2007 or 1998 (not shown) but prevailing northerly winds persisted during the melt season facilitating a continuous flux of MYI from the QEI directly across the WPC preventing it from clearing completely (Figure 4). A long melt season alone is therefore not sufficient to significantly clear the WPC region of the NWP if MYI replenishment occurs from the QEI.

## 4. Conclusions

[17] The CAA and every sub-region within exhibited negative trends for average September total ice which corresponded to an increase in the melt season duration. The longer melt season has significantly reduced the inventory of FYI at the end of the melt season. Average September MYI decreases however are less significant despite a trend toward a longer melt season that can be attributed to increases in MYI dynamic import from the Arctic Ocean. Therefore, as the transition to a summer-time sea ice free Arctic continues it should be noted that the supply of MYI from the Arctic Ocean to the CAA may reduce but it is unlikely to stop.

[18] The WPC, which contains the most direct route through the NWP, will also continue to be susceptible to MYI and in the short-term this may result only in a minor lengthening of the shipping season. In order for WPC route through the NWP to clear similar to 2007 several factors must be in place: i) a weakened MYI cover, ii) anomalously warm temperatures facilitating rapid melt, and iii) a SLP pattern preventing MYI transiting through BMC from crossing the WPC.

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